TITLE OF THE INVENTION

OPTICAL TRANSMISSION SYSTEM

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to an optical transmission system, and more particularly to a system for transmitting an optical signal from a transmitter to a receiver through a multi-mode fiber.

Description of the Background Art

[0002] The development in technologies in recent years has produced optical fibers which satisfy broadband requirements as well as low loss requirements. As a result, optical fibers are being introduced in the backbone systems for interconnecting exchange systems on a network (e.g., the Internet). Optical fibers are considered promising for future applications in access systems for interconnecting exchanges with households, and also applications in home networks.

[0003] Optical fibers can be generally classified in two types based on their characteristics: single mode fibers (hereinafter referred to as "SMFs") and multi-mode fibers (hereinafter referred to as "MMFs"). In a SMF, both the core and the cladding are made of silica (SiO_2). A SMF has a core diameter as small as about 10 μm. Furthermore, a SMF features a broad transmission

bandwidth because it only allows a particular mode to be propagated therethrough. Therefore, SMFs have mainly enjoyed developments for long-distance and broadband transmission purposes in the backbone systems, and have gained wide prevalence there.

[0004] On the other hand, a MMF has a core diameter of 50 μm to 1 mm, which is greater than the core diameter of a SMF. MMFs can be classified in several types based on the materials of the core and cladding. MMFs whose core and cladding are both made of silica are called GOFs (Glass Optical Fibers). MMFs whose core is made of silica, and whose cladding is made of a polymer, are called PCFs (Polymer Clad Fibers). MMFs whose core and cladding are both plastic are called POFs (Plastic Optical Fibers).

[0005] A MMF has a plurality of propagation modes (i.e., optical paths). FIG. 12 is a schematic diagram illustrating a plurality of propagation modes. In FIG. 12, a MMF 73 has a core 71 and a cladding 72. The entirety of light travels through the core 71 while being repeatedly reflected at the boundary F_{bd} between the core 71 and the cladding 72 (TIR: Total Internal Reflection). Therefore, modes which are closer to being parallel to the boundary F_{bd} will travel longer distances over the fiber axis between one reflection and the next reflection. Such modes (denoted by dot-dash lines) are referred to as lower-order modes (M_{LO}). On the other hand, modes which travel shorter distances over the fiber axis between one reflection and the next reflection (denoted by double-dot-dash lines) are referred to as higher-order modes (M_{HI}).

A higher-order mode M_{HI} constitutes a relatively large angle with respect to the fiber axis. Therefore, given a fixed length of the MMF 73, a higher-order mode M_{HI} will experience a larger number of reflections at the boundary F_{bd} than a lower-order mode M_{LO}, thus presenting an optical path which is different from that of the lower-order mode M_{LO} ("optical path difference"). Due to optical path differences, different modes require different amounts of time to travel from an input plane to an output plane of the MMF 73.

[0006] An optical signal is transmitted through an optical fiber in the form of a pulse sequence. Since each mode in the optical signal has its own inherent propagation speed, a pulse sequence which is contained in a lower-order mode M_{LO} (which has a relatively short propagation time) and the same pulse sequence which is contained in a higher-order mode M_{HI} (which has a relatively long propagation time) will arrive at the receiving end at different times, although directed to the same information. As a result, the receiving end of the information may not be able to correctly receive the signal. This phenomenon, known as mode dispersion, is a factor which considerably constrains the transmission bandwidth of a MMF as compared to that of a SMF.

[0007] A transmission bandwidth of an optical fiber is usually represented as a product of a data rate for optical signals transmitted therethrough and a transmission distance (e.g., Mbps $\times$ km). The transmission distance must be decreased as the data

rate is increased. In order to increase the transmission distance, the data rate must be lowered. The influence of mode dispersion also becomes more significant as the data rate is increased, or as the transmission distance is increased. Therefore, conventional optical transmission systems employing MMFs have a problem in that the transmission distance must be compromised in order to obtain a necessary data rate.

[0008] However, MMFs are less expensive than SMFs. Therefore, on the bare comparison, an optical transmission system employing MMFs should be able to be constructed inexpensively as compared to a system employing SMFs. Moreover, since the core diameter of a MMF is greater than that of a SMF, it is relatively easy to align the axes of two MMFs with each other. This helps relaxing the mounting precision of a connector for interconnecting MMFs. Thus, MMFs can greatly contribute to the construction of a low-cost optical transmission system. Therefore, MMFs are preferred for optical transmission over a distance which is short enough for the mode dispersion effects to be negligible.

[0009] In order to take advantage of the aforementioned features of MMFs, a number of techniques for reducing the influence of mode dispersion in MMFs and for improving the transmission bandwidth of an optical transmission system have been proposed. With reference to FIGS. 13 and 14, a technique disclosed in Japanese Patent Laid-Open Publication No. 10-227935 will be described. FIG. 13 is a block diagram illustrating the overall structure of

a conventional optical transmission system S_{cv}. As shown in FIG. 13 , the optical transmission system S_{cv} includes a light source 82 having a lens 81, a MMF 83, a mode separator 84, and a receiver 85. FIG. 14 is a schematic diagram illustrating the optical coupling between the lens 81 and the MMF 83 shown in FIG. 13. As shown in FIG. 14, the lens 81 and the MMF 83 are disposed so as to attain a maximum coupling efficiency. Specifically, the MMF 83 is affixed in such a manner that an optical axis A_{lz} (denoted by a dot-dash line) of the lens 81 and a fiber axis A_{fr} (denoted by a double-dot-dash line) of the MMF 83 are on a single straight line, and that an intersection between an input plane F_{in} (i.e., one of the end faces of the MMF 83) and the fiber axis A_{fr} coincides with a focal point Z_{fp} of the lens 81.

[0010] In the above-described optical transmission system S_{cv}, an optical signal from the lens 81 is focused on the input plane F_{in} of the MMF 83, and therefore efficiently enters the MMF 83 with small coupling losses. Thereafter, the optical signal suffers increasingly more influence of mode dispersion as it is propagated through the core of the MMF 83. As a result, an optical signal having a plurality of modes associated with different propagation delay amounts goes out at an output plane F_{out} of the MMF 83 (i.e., the end opposite to the input plane F_{in}). The optical signal outputted from the MMF 83 enters the mode separator 84, where only the necessary mode(s) is selected. Thereafter, the receiver 85 receives the optical signal which has been subjected

to the selection at the mode separator 84. Thus, the receiver 85 is allowed to receive an optical signal with a reduced influence of mode dispersion, whereby the transmission bandwidth of MMF 83 is improved.

[0011] However, the mode separator 84, which is essentially an optical system comprising a number of lenses and mirrors, may be expensive. Moreover, the use of such an optical system complicates the overall structure of the optical transmission system S_{cv}. Furthermore, the optical axis alignment between components of the mode separator 84 requires high precision. This presents a problem because it takes considerable cost to construct and maintain the conventional optical transmission system S_{cv}.

[0012] There is an additional problem in that it is difficult to improve the mode selection efficiency of the mode separator 84. As used herein, the "mode selection efficiency" is a ratio of the output power to the input power of the mode separator 84 for a given mode. If the mode selection efficiency is poor, the input power for the receiver 85 is diminished, so that it may become necessary to enhance the power of the optical signal originating from the light source 82 and/or the photodetection sensitivity of the receiver 85, or to provide an optical amplifier subsequent to the mode separator 84, leading to increased cost for constructing and maintaining the conventional optical transmission system S_{cv}.

SUMMARY OF THE INVENTION

[0013] Therefore, an object of the present invention is to provide a low-cost optical transmission system employing multi-mode fibers which can minimize the influence of mode dispersion.

[0014] The present invention has the following features to attain the object above.

The present invention is directed to an optical transmission system for transmitting an optical signal from a transmitter to a receiver through a multi-mode fiber. The transmitter comprises: a light emission element for generating an optical signal, and at least one lens for converging the optical signal generated by the light emission element to focus at a focal point. The optical signal converged by the at least one lens enters an input plane of the multi-mode fiber to propagate through the multi-mode fiber. The receiver comprises a light receiving element for receiving the optical signal outputted from the multi-mode fiber. The input plane is placed at a position other than the focal point.

[0015] These and other objects, features, aspects and advantages of the present invention will become more apparent from the following detailed description of the present invention when taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] FIG. 1 is a block diagram illustrating the overall

structure of an optical transmission system S_a according to a first embodiment of the present invention;

FIG. 2 is a schematic diagram illustrating optical coupling in the optical transmission system S_a shown in FIG. 1;

FIG. 3 is a schematic diagram showing an eye pattern of an optical signal OS_{out1} shown in FIG. 1;

FIG. 4 is a graph showing the eye opening factor R and the output power P of the optical signal OS_{out1} relative to the distance Z_1 shown in FIG. 2;

FIG. 5 is a schematic diagram illustrating a numerical aperture ($=\sin\alpha$) of a transmitter 11 shown in FIG. 1;

[0017] FIG. 6 is a schematic diagram illustrating an incident light propagation plane F_{ipr};

FIG. 7 is a block diagram illustrating the overall structure of an optical transmission system S_b according to a second embodiment of the present invention;

FIG. 8 is a schematic diagram illustrating optical coupling in the optical transmission system S_b shown in FIG. 7;

FIG. 9 is a schematic diagram illustrating a higher-order outgoing angle γ_{HI} and a lower-order outgoing angle γ_{LO};

FIG. 10 is a schematic diagram illustrating an output light propagation plane F_{opr};

[0018] FIG. 11 is a block diagram illustrating the overall structure of an optical transmission system S_c according to a third

embodiment of the present invention;

FIG. 12 is a schematic diagram illustrating general examples of a higher-order mode M_{HI} and a lower-order mode M_{LO};

FIG. 13 is a block diagram illustrating the overall structure of a conventional optical transmission system S_{cv}; and

FIG. 14 is a schematic diagram illustrating optical coupling between a light source 82 and a multi-mode fiber 83 shown in FIG. 13.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0019] (first embodiment)

FIG. 1 is a block diagram illustrating the overall structure of an optical transmission system S_a according to a first embodiment of the present invention. FIG. 2 is a schematic diagram illustrating optical coupling in the optical transmission system S_a shown in FIG. 1. The optical transmission system S_a includes a transmitter 11, a multi-mode fiber (MMF) 12, and a receiver 13.

[0020] As shown in FIG. 1, the transmitter 11 includes a light emission element 111, at least one lens 112, and a receptacle 113. The light emission element 111, which typically comprises a laser diode or a light-emitting diode, is driven by an input electrical signal ES_{in} to generate an optical signal OS_{in}. The lens 112, whose optical axis is aligned with that of the light emission element 111, allows the optical signal OS_{in} generated by the light emission element 111 to pass therethrough. As shown in FIG. 2, in the

present embodiment, a vertex Z_0 of the lens 112 is defined as the one of the two intersections between the optical axis A_{lz} and the surface F_{lz} of the lens 112 which is located farther away from the light emission element 111. A focal point Z_{fp} of the lens 112 is defined as a position along the optical axis A_{lz} where the optical signal OS_{in}, which has passed through the lens 112, focuses. The receptacle 113 shown in FIG. 1 will be described later.

[0021] In FIG. 1, the MMF 12 is a glass fiber of a graded index type, a polymer cladding fiber, or a plastic optical fiber. As shown in FIG. 2, the MMF 12 includes a core 121 and a cladding 122. A connector plug 123 is affixed to one end of the MMF 12 around the outer periphery thereof. The connector plug 123 is fitted into the receptacle 113 of the transmitter 11. As a result, as shown in FIG. 2, the fiber axis A_{fr} of the MMF 12 and the optical axis A_{lz} of the lens 112 are aligned with each other, and one of the end faces of the core 121 (hereinafter referred to as an "input plane F_{in}") is positioned at a predetermined distance Z_1 from the vertex Z_0 of the lens 112 along the fiber axis A_{fr}. The distance Z_1 is set at a value which is not equal to the distance from the vertex Z_0 to the focal point Z_{fp}, and preferably set at a value greater than the distance from the vertex Z_0 to the focal point Z_{fp}.

[0022] As shown in FIG. 2, a connector plug 124 is affixed to the other end of the core 121 around the outer periphery thereof. The optical signal OS_{in} which has passed through the lens 112 enters

the input plane F_{in} of the MMF 12 having the above-described structure. As described in more detail later, since the input plane F_{in} is at the distance Z_1 from the vertex Z_0, the optical signal OS_{in} entering the input plane F_{in} is propagated through the core 121 without being substantially affected by the influence of mode dispersion, so as to go out from the other end (hereinafter referred to as the "output plane F_{out}") of the core 121 as an optical signal OS_{out1}.

[0023] Referring back to FIG. 1, the receiver 13 includes a receptacle 131 and a light receiving element 132. The connector plug 124 affixed to the MMF 12 is fitted into the receptacle 131, thereby connecting the receiver 13 to the MMF 12. The light receiving element 132, which preferably comprises a Si PIN photodiode (hereinafter referred to as a "Si PIN PD"), has a face (hereinafter referred to as the "light-receiving plane F_{PD1}") at which the optical signal OS_{out1} outputted from the MMF 12 enters. The light-receiving plane F_{PD1} has an area nearly equal to or greater than the output plane F_{out}. When the receiver 13 is connected to the MMF 12, the light-receiving plane F_{PD1} is positioned so as to oppose the output plane F_{out} of the MMF 42 in a parallel orientation. The light receiving element 132 having the above-described structure converts the optical signal OS_{out1} entering the light-receiving plane F_{PD1} into an electrical signal ES_{out1} which represents the same information as that represented by the electrical signal ES_{in}.

[0024] The reason why a Si PIN PD is preferably used as the light receiving element 132 is that a Si PIN PD generally has a large light-receiving plane F_{PD1}. However, the light receiving element 132 may be composed of a photodiode other than a Si PIN PD because the size of the light-receiving plane F_{PD1} is not essential to the present embodiment.

[0025] Next, the distance Z_1, which is employed in a characteristic manner in the present embodiment, will be described. In order to determine the distance Z_1, the applicant performed an experiment as follows by using the above-described optical transmission system S_a. The experiment was carried out under the following conditions: As the light emission element 111, a light emission element capable of emitting light having a power of 1.8 mW when a DC current of 30 mA is injected thereto was employed. Two PCFs (Polymer Clad Fibers) having respectively different lengths were prepared as MMFs 12 in order to enable experiments for short-distance transmission and long-distance transmission. More specifically, the MMF 12 for short-distance transmission had a length L_{fr} of 2.0 m, and the MMF 12 for long-distance transmission had a length L_{fr} of 100 m. The core 121 of each MMF 12 was composed of silica (SiO_2), and had a diameter (hereinafter referred to as the "core diameter") ϕ_{cr} (see FIG. 2) of 200 μm. The cladding 122 was composed of a polymer such as a methacrylic resin (PMMA), with a diameter of 230 μm.

[0026] Next, an eye opening factor R and an output power P,

which were the subjects of measurement under the experiment conducted by the applicant, will be described. FIG. 3 is a schematic diagram showing an eye pattern of the optical signal OS_{out1} of the MMF 12. The eye opening factor R is defined as a ratio of a minimum value V_{pp1} to a maximum value V_{pp2} of amplitude of the eye pattern as shown in FIG. 3, or V_{pp1}/V_{pp2}. From the eye opening factor R as defined above, a transmission bandwidth of the optical transmission system S_a can be determined. The output power P is a light power of the optical signal OS_{out1} from the MMF 12.

[0027] Under the above experimental conditions, the applicant measured the characteristics of the eye opening factor R and the output power P with respect to the position Z_1 of the input plane F_{in}, by means of measurement devices such as a power meter. As a result, measurement results as shown in FIG. 4 were obtained. In FIG. 4, the horizontal axis Z_1, which is identical to the optical axis A_{1z} described above, represents distance to the input plane F_{in} as taken from the position of the vertex Z_0 of the lens 112. Herein, the position of the vertex Z_0 of the lens 112 is defined as $Z_1=0$. In other words, FIG. 4 shows the manner in which the eye opening factor R and the output power P change as the input plane F_{in} of the MMF 12 is gradually pulled away from the vertex Z_0 along the optical axis A_{1z} (i.e., the "Z_1" axis).

[0028] More specifically, FIG. 4 shows the eye opening factor R (hereinafter referred to as the "eye opening factor R_{sd}"; shown

by "●" symbols) and the output power P (hereinafter referred to as the "output power P_{sd}"; shown by "○" symbols") of the optical signal OS_{out1} when the length L_{fr} of the MMF 12 is 2 m. FIG. 4 also shows the eye opening factor R (hereinafter referred to as the "eye opening factor R_{ld}"; shown by "▲" symbols) and the output power P (hereinafter referred to as the "output power P_{ld}"; shown by "△" symbols") of the optical signal OS_{out1} when the length L_{fr} is 100 m.

[0029] Since the maximum values of the output power P_{sd} and P_{ld} are both observed when Z_1 is in the range from 1.0 mm to 1.5 mm, it can be seen that the optical signal OS_{in} having passed through the lens 112 is focused at a focal point Z_{fp} which is in this range. In this sense, the range of Z_1 from 1.0 mm to 1.5 mm will be referred to as a "focal range" D_{fp} (see regions hatched with dots in FIG. 4). Note, however, that the eye opening factor R_{ld} is considerably deteriorated in the focal range D_{fp}. The eye pattern (FIG. 3) of the optical signal OS_{out1} having such a deteriorated eye opening factor R_{ld} reveals a significant difference between the minimum value V_{pp1} and the maximum value V_{pp2} in amplitude. This indicates that it is difficult to transmit the optical signal OS_{in} over a long distance (e.g., 100 m) when the input plane F_{in} of the MMF 12 is set within the focal range D_{fp}.

[0030] On the other hand, in FIG. 4, the eye opening factor R_{sd} is substantially constant regardless of the value of Z_1, unlike the eye opening factor R_{ld}. Such differences in the characteristics

of the eye opening factor R indicates the facts that the influence of mode dispersion varies depending on the value of Z_1 and that the influence of mode dispersion becomes more outstanding as the transmission distance of the optical signal OS_{in} increases.

[0031] Referring back to FIG. 14, in the conventional optical transmission system S_{cv}, the input plane F_{in} of the MMF 83 is positioned at the focal point Z_{fp} so as to maximize the coupling efficiency with the MMF 83 (i.e., so as to allow the optical signal to enter the MMF 83 with minimum coupling losses). However, it should now be clear from the characteristic curves shown in FIG. 4 that, when the input plane F_{in} is positioned at the focal point Z_{fp}, the optical signal OS_{in} suffers severer influence of mode dispersion as the MMF 12 becomes longer. This indicates that, in the conventional optical transmission system S_{cv}, the transmission bandwidth is under the constraints imposed by mode dispersion.

[0032] The above findings can be theorized as follows. Prior to the following explanation, three parameters used therein, i.e., the numerical aperture (hereinafter "NA_s") of the transmitter 11, the numerical aperture (hereinafter "NA_f") of the MMF 12 and the numerical aperture (hereinafter "NA_{in}") of the optical signal OS_{in} entering and propagated through the MMF 12, will be first described.

[0033] FIG. 5 is a schematic diagram illustrating the NA_s of the transmitter 11 shown in FIG. 1. As shown in FIG. 5, the optical signal OS_{in}, which once focuses at the position Z_{fp}, propagates

while spreading at an angle of α with respect to the optical axis A_{1z}. The NA_s, which is a measure of such spread, can be expressed by equation (1) below:

$$NA_s = \sin\alpha \quad \cdots (1)$$

[0034] The value of NA_s increases as the once-focused optical signal OS_{in} has a greater expanse. The value of NA_s is within the range $0 < NA_s \leq 1$.

[0035] In the light entering the MMF 12, the only components which propagate to the output plane F_{out} are those within a certain range of angles (hereinafter referred to as the "propagation angles" of the MMF 12). Based on the largest propagation angle of the MMF 12, named β_{max}, the NA_f can be expressed by equation (2) below:

$$NA_f = \sin\beta_{max} \quad \cdots (2)$$

[0036] Usually, the above-defined NA_f is determined by the refractive indices of the core 121 and the cladding 122, and is a parameter which is independent of the aforementioned NA_s. If light having a numerical aperture greater than the NA_f enters the input plane F_{in}, any components which spread outside the aforementioned range of propagation angles of the MMF 12 will be

transmitted through to the exterior of the MMF 12. On the other hand, if the optical signal OS_{in} has a numerical aperture smaller than the NA_f, then all components of the light will propagate through the core 121 as explained above. Moreover, since the optical signal OS_{in} has a smaller numerical aperture than the NA_f in this case, the higher-order modes in the optical signal OS_{in} are decreased, so that the mode dispersion can be reduced.

[0037] Moreover, in the optical transmission system S_a, once the position Z_1 of the input plane F_{in} is determined, only those components of the optical signal OS_{in} having the NA_s which are within a predetermined range of angles (which in the present embodiment are referred to as the "reachable angles", i.e., angles reachable to the MMF 12) can actually enter the input plane F_{in}. Any light components which lie outside the range of reachable angles, which do not enter the input plane F_{in}, will not be propagated through the core 121. Furthermore, due to the NA_f of the MMF 12, all components of the optical signal OS_{in} may not always be propagated to the output plane F_{out} even if it enters the input plane F_{in}. Assuming that the components of the optical signal OS_{in} which enter the input plane F_{in} and which are propagated through the MMF 12 to the output plane F_{out} have a largest incident angle of β_{th}, the aforementioned NA_{in} can be expressed by equation (3) below:

$$NA_{in} = \sin \beta_{th} \quad \cdots (3)$$

[0038] In general, mode dispersion is more reduced as the NA_{in} expressed by equation (3) decreases.

[0039] FIG. 6 is a schematic diagram illustrating an incident light propagation plane F_{ipr} (defined below), which helps detailed explanation of the NA_{in}. In the following description, it is assumed that the input plane F_{in} (shown hatched with oblique lines in FIG. 6) has an area S_f; the input plane F_{in} has a diameter (i.e., core diameter) ϕ_{cr} as shown in FIG. 2; and the incident light propagation plane F_{ipr} (shown hatched with dots in FIG. 6) has an area $S(Z_1)$. First, a geometric definition of the incident light propagation plane F_{ipr} will be given. The optical signal OS_{in} which has passed through the lens 112 (not shown) converges until reaching the focal point Z_{fp}, and thereafter diverges in a conical shape. When one draws an imaginary plane at a distance of Z_1 from the vertex Z_0, such that the imaginary plane is perpendicular to the optical axis A_{lz}, the incident light propagation plane F_{ipr} is defined as a cross-section of the optical signal OS_{in} taken at the imaginary plane. As will be clear from FIG. 6, the ratio of the area $S(Z_1)$ to the area S_f changes depending on the position Z_1 of the input plane F_{in}. Thus, it is possible to adjust the NA_{in} by changing the position Z_1 of the input plane F_{in}; in other words, the NA_{in} is a function of Z_1, and can be expressed as $NA_{in}(Z_1)$. Thus, by changing the position Z_1 of the input plane F_{in}, it is possible to control the mode dispersion, which affects the transmission distance and the data rate of the optical signal OS_{in}.

[0040] First, the case in which the NA_s is equal to or less than the NA_f will be considered. In this case, all of the components of the optical signal OS_{in} which have passed through the lens 112 and which enters the core 121 are propagated to the output plane F_{out}. If $S(Z_1)$ is equal to or greater than S_f, $NA_{in}(Z_1)$ decreases as Z_1 increases, as expressed by equation (4) below:

$$\begin{aligned} NA_{in}(Z_1) &= \sin \beta_{th} \\ &= \sin\left(\left(\arctan\left(\frac{\phi_{cr}}{2 \cdot \left|Z_1 - Z_{fp}\right|}\right)\right)\right) \quad ; S(Z_1) \geq S_f \quad \cdots (4) \end{aligned}$$

[0041] On the other hand, if $S(Z_1)$ is smaller than S_f, all of the optical signal OS_{in} which has passed through the lens 112 enters the input plane F_{in}, and is propagated to the output plane F_{out}. In this case, the NA_{in} can be expressed by equation (5) below.

$$NA_{in}(Z_1) = \sin \beta_{th} = NA_s \quad ; S(Z_1) < S_f \quad \cdots (5)$$

[0042] Next, the case in which NA_s is greater than NA_f will be considered. In this case, even if all of the optical signal OS_{in} which has passed through the lens 112 enters the input plane F_{in}, any components (modes) thereof which fall outside the NA_f cannot be propagated through the core 121. Therefore, $NA_{in}(Z_1)$ is fixed such that $NA_{in}(Z_1) = NA_f$. However, as Z_1 increases therefrom so that $NA_{in}(Z_1) < NA_f$ is satisfied, thereafter $NA_{in}(Z_1)$ decreases with an

increase in Z_1, as can be expressed by equation (6) below:

$$NA_{in}(Z_1) = \sin \beta_{th} = \sin\left(\left(\arctan\left(\frac{\phi_{cr}}{2 \cdot \left|Z_1 - Z_{fp}\right|}\right)\right)\right) \leq NA_f \quad \cdots (6)$$

[0043] As described above, by adjusting the position Z_1, it is possible to reduce the NA_{in} (i.e., $NA_{in}(Z_1)$). Thus, the influence of mode dispersion, which is a problem associated with a long-distance transmission of the optical signal OS_{in}, can be minimized.

[0044] In an actual implementation of the optical transmission system S_a, the determination of the position Z_1 must be made while considering both the output power P from the MMF 12 and the eye opening factor R as design requirements. The reason is that, as the influence of mode dispersion is reduced by increasing the value of Z_1, the coupling losses between the transmitter 11 and the MMF 12 increase, making it difficult to obtain the required output power P.

[0045] For example, let us assume that the three following design requirements are given in the optical transmission system S_a shown in FIG. 1: MMF 12 has a length L_{fr} of 100 m; the output power P is equal to greater than 0.1 mW; and the eye opening factor R is equal to greater than 50%. Under this assumption, it can be seen from the eye opening factor R_{1d} characteristics (represented

by ▲) and the output power P_{1d} characteristics (represented by △) shown in FIG. 4 that the value of Z_1 is preferably in the range from 2.0 mm to 2.5 mm (see the region hatched with oblique lines in FIG. 4). Note that a Z_1 value of at least 2.0 mm or more can be employed in order to simply reduce the influence of mode dispersion without considering any other design requirements. Thus, the present optical transmission system S_a allows the influence of mode dispersion in the MMF 12 to be reduced based on the adjustment of the position Z_1, whereby the transmission bandwidth of the MMF 12 can be broadened. This eliminates the need for a mode separator 84 (see FIG. 13) in the optical transmission system S_a, unlike in the conventional optical transmission system S_{cv}. Thus, a low-cost optical transmission system S_a can be provided according to the present embodiment of the invention.

[0046] Note that the value of Z_1 is not always limited to 2.0 mm or above, but may vary depending on design requirements such as the length L_{fr} of the MMF 12, the output power P, and the eye opening factor R . In general, the influence of mode dispersion becomes more outstanding as the transmission distance (length L_{fr}) increases. Stated otherwise, the value of Z_1 decreases as the transmission distance decreases.

[0047] (second embodiment)

FIG. 7 is a block diagram illustrating the overall structure of an optical transmission system S_b according to a second

embodiment of the present invention. FIG. 8 is a schematic diagram illustrating how optical coupling occurs in the optical transmission system S_b shown in FIG. 7. The optical transmission system S_b is identical to the optical transmission system S_a except that the transmitter 11 and the receiver 13 are replaced by a transmitter 21 and a receiver 22. Accordingly, any component elements in the optical transmission system S_b which find their counterparts in the optical transmission system S_a will be denoted by the same reference numerals as those used in FIGS. 1 and 2, and the descriptions thereof are omitted.

[0048] With reference to FIG. 7, the transmitter 21 is identical to the transmitter 11 shown in FIG. 1 except that the receptacle 113 is replaced by a receptacle 211. Accordingly, any component elements in the transmitter 21 which find their counterparts in the transmitter 11 will be denoted by the same reference numerals as those used in FIG. 1, and the descriptions thereof are omitted. The connector plug 123 which is affixed to the input plane F_{in} of the MMF 12 is fitted into the receptacle 211. As a result, as shown in FIG. 8, the fiber axis A_{fr} of the MMF 12 and the optical axis A_{lz} of the lens 112 are aligned with each other, and the input plane F_{in} is positioned substantially at the focal point Z_{fp} so as to maximize the coupling efficiency between the lens 112 and the MMF 12. In this aspect, the transmitter 21 is clearly distinct from the transmitter 11 shown in FIG. 1. Therefore, an optical signal OS_{in} entering the input plane F_{in} is propagated trough the

core 121 while being affected by mode dispersion, so as to be outputted from the output plane F_{out} as an optical signal OS_{out2}.

[0049] As shown in FIG. 7, the receiver 22 includes a receptacle 221 and a light receiving element 222. The connector plug 124 which is affixed to the MMF 12 is fitted into the receptacle 221. The light receiving element 222 which preferably comprises a Si PIN PD, has a face (hereinafter referred to as the "light-receiving plane F_{PD2}") at which the optical signal OS_{out2} outputted from the MMF 12 enters. In the present embodiment, it is assumed that the light-receiving plane F_{PD2} has a circular shape for the sake of explanation. As shown in FIG. 8, when the receiver 22 is connected to the MMF 12, the light-receiving plane F_{PD2} having the above-described structure opposes the output plane F_{out} of the MMF 12 in a parallel orientation, with a distance Z_2 therebetween. Furthermore, a central axis A_{PD} of the light-receiving plane F_{PD2} is aligned with the fiber axis A_{fr}. Thus, as shown in FIG. 7, the light receiving element 222 converts the optical signal OS_{out2} entering the light-receiving plane F_{PD2} into an electrical signal ES_{out2} which represents the same information as that represented by the electrical signal ES_{in}.

[0050] As described above, according to the present embodiment, the input plane F_{in} is positioned at the focal point Z_{fp}, so that the optical signal OS_{in} entering the input plane F_{in} suffers severer influence of mode dispersion than in the first embodiment. As a result, the respective modes in the optical signal OS_{in} which

simultaneously enter the input plane F_{in} arrive at the output plane F_{out} at respectively different times. Therefore, the outputted optical signal OS_{out2} has a relatively "closed" eye pattern. When all modes in the outputted optical signal OS_{out2} enter the light-receiving plane F_{PD2}, the receiver 22 cannot correctly receive the information which is represented by the electrical signal ES_{in}.

[0051] FIG. 9 is a schematic diagram illustrating a higher-order outgoing angle γ_{HI} of a higher-order mode M_{HI} and a lower-order outgoing angle γ_{LO} of a lower-order mode M_{LO}, both contained in the optical signal OS_{out2} shown in FIG. 8. As shown in FIG. 9, the higher-order mode M_{HI} and the lower-order mode M_{LO} go out at respectively different angles, i.e., the higher-order outgoing angle γ_{HI} and the lower-order outgoing angle γ_{LO}, with respect to the fiber axis A_{fr}. The lower-order outgoing angle γ_{LO} is smaller than the higher-order outgoing angle γ_{HI}. Therefore, the higher-order mode M_{HI} will travel farther away from the fiber axis A_{fr} as the value of Z_2 increases. Accordingly, the value of Z_2 can be adjusted to prevent the higher-order mode M_{HI} from entering the light-receiving plane F_{PD}, so that the light receiving element 222 will selectively receive only the lower-order mode M_{LO}.

[0052] The aforementioned selective reception can be explained as follows. First, the parameters employed in the following explanation, i.e., the outgoing numerical aperture (hereinafter referred to as "NA_{out}") of the MMF 12 and the numerical aperture (hereinafter referred to as "NA_{PD}") of the light-receiving plane

F_{PD2}, will be described.

[0053] As seen above, modes with various outgoing angles go out from the output plane F_{out} of the MMF 12. Based on the largest angle among such outgoing angles, named γ_{max}, the NA_{out} can be expressed by equation (7) below:

$$NA_{out} = \sin \gamma_{max} \cdots (7)$$

[0054] Note that, since the input plane F_{in} is positioned at the focal point Z_{fp} in the present embodiment, the NA_{out} is substantially the same value as the $NA_{in}(Z_{fp})$ obtained from equations (4) to (6) above.

[0055] Moreover, in accordance with the optical transmission system S_b, once the position Z_2 is determined, only those modes in the outputted optical signal OS_{out2} having the NA_{out} which are within a predetermined range of angles (which in the present embodiment are referred to as the "reachable angles", i.e., angles reachable to the light-receiving plane F_{PD2}) can actually reach the light-receiving plane F_{PD2}. Assuming that the modes in the optical signal OS_{out2} outputted from the output plane F_{out} which enter the light-receiving plane F_{PD2} have a largest outgoing angle of γ_{th}, the aforementioned NA_{PD} can be expressed by equation (8) below:

$$NA_{PD} = \sin \gamma_{th} \cdots (8)$$

[0056] FIG. 10 is a schematic diagram illustrating an output light propagation plane F_{opr} (defined below), which helps detailed explanation of the NA_{PD}. In the following description, it is assumed that the output plane F_{out} (shown cross-hatched in FIG. 10) has an area S_f; the output plane F_{out} has a diameter (i.e., core diameter) ϕ_{cr}; and the light-receiving plane F_{PD2} (shown hatched with oblique lines in FIG. 10) has an area S_{PD}. The light-receiving plane F_{PD2} is assumed to have a circular shape in the present embodiment. Under this assumption, it is further assumed that the light-receiving plane F_{PD2} has a diameter ϕ_{PD}. It is also assumed that the output light propagation plane F_{opr} (shown hatched with dots in FIG. 10) has an area $S(Z_2)$. First, a geometric definition of the output light propagation plane F_{opr} will be given. The optical signal OS_{out2} outputted from the MMF 12 diverges in a radial manner. When one draws an imaginary plane at a distance of Z_2 from the output plane F_{out}, such that the imaginary plane is perpendicular to the optical axis A_{1z}, the output light propagation plane F_{opr} is defined as a cross-section of the aforementioned outputted optical signal OS_{out2} taken at the imaginary plane. It is possible to adjust the largest outgoing angle γ_{th}, and hence the NA_{PD}, by changing the position Z_2 of the output plane F_{out}; in other words, the NA_{PD} is a function of Z_2,

and can be expressed as $NA_{PD}(Z_2)$. Thus, by changing the distance Z_2 of the light-receiving plane F_{PD} from the output plane F_{out}, it can be ensured that the light receiving element 222 selectively receives only the lower-order mode M_{LO} (shown in FIG. 9) while avoiding the higher-order mode M_{HI}, which would cause the outgoing optical signal OS_{out2} to have a relatively closed eye pattern. As a result, the light receiving element 222 can generate the electrical signal ES_{out2} representing the same information as that represented by the electrical signal ES_{in}.

[0057] The $NA_{PD}(Z_2)$ will be described in more detail. First, the case where $S(Z_2)$ is greater than S_{PD} will be considered. In this case, $NA_{PD}(Z_2)$ decreases as the value of Z_2 increases, as expressed by equation (9) below:

$$
\begin{aligned}
NA_{PD}(Z_2) &= \sin \gamma_{th} \\
&= \sin\left(\left(\arctan\left(\frac{\phi_{PD} - \phi_{cr}}{2 \cdot Z_2}\right)\right)\right) \quad ;\ S(Z_2) \geq S_{PD} \quad \cdots (9)
\end{aligned}
$$

[0058] The smaller the outgoing angle of a given mode in the optical signal OS_{out2} outputted from the MMF 12, the lower the order of the mode. Therefore, by setting the light-receiving plane F_{PD2} at the distance Z_2 from the output plane F_{out} along the fiber axis A_{fr}, the light receiving element 222 can selectively receive the lower-order mode M_{LO} while avoiding the higher-order mode M_{HI}. Thus, according to the present embodiment, without requiring a mode

separator 84 as shown in FIG. 13, the influence of mode dispersion in the MMF 12 can be reduced by simply adjusting the position Z_2, and the transmission bandwidth of the MMF 12 can be broadened. As a result, a low-cost optical transmission system S_b with a broad transmission bandwidth can be provided.

[0059] On the other hand, in the case where $S(Z_2)$ is smaller than S_{PD}, all of the modes contained in the optical signal OS_{out2} outputted from the MMF 12 will enter the light-receiving plane FDP2. In other words, $NA_{PD}(Z_2)$ takes the same value as NA_{out}, as expressed by equation (10) below:

$$NA_{PD}(Z_2) = \sin \gamma_{th} = NA_{out} \quad ; S(Z_2) < S_{PD} \quad \cdots (10)$$

[0060] Note that $S(Z_2)$ being smaller than S_{PD} means that ϕ_{cr} is greater than ϕ_{PD} and that the light-receiving plane F_{PD2} is in proximity of the output plane F_{out}. Moreover, in this case, the light receiving element 222 cannot selectively receive only the lower-order mode M_{LO}. This fact also rationalizes the need for setting the light-receiving plane F_{PD2} away from the output plane F_{out}.

[0061] In an actual implementation of the optical transmission system S_b, the determination of the distance Z_2 described above must be made while considering both the input power to the light-receiving plane F_{PD2} and the eye opening factor of the optical signal F_{out} entering the light-receiving plane F_{PD2} as design

requirements. The reason is that, as the influence of mode dispersion is reduced by increasing the value of Z_2, the coupling losses between the transmitter 11 and the MMF 12 increase, making it difficult to obtain the required input power P. Furthermore, the determination of the distance Z_2 described above must be made while considering the length L_{fr} of the MMF 12 and the data rate of the optical signal OS_{in}, which are design requirements of the optical transmission system S_b. In other words, as the length L_{fr} and the data rate become greater, the influence of mode dispersion becomes more outstanding, therefore requiring a greater Z_2 value.

[0062] (third embodiment)

FIG. 11 is a block diagram illustrating the overall structure of the optical transmission system S_c according to a third embodiment of the present invention. In short, the optical transmission system S_c shown in FIG. 11 combines the features of the first and second embodiments, and comprises the transmitter 11, the MMF 12, and the receiver 22. Accordingly, any component elements in FIG. 11 which find their counterparts in FIG. 1 or 7 will be denoted by the same reference numerals as those used therein, in order to simplify description.

[0063] As shown in FIG. 11, the connector plug 123 is fitted into the receptacle 113 of the transmitter 11. As a result, as described with reference to FIG. 2, the fiber axis A_{fr} of the MMF 12 and the optical axis A_{lz} of the lens 112 are aligned, and the

input plane F_{in} of the core 121 is positioned at a predetermined distance Z_1 from the vertex Z_0 of the lens 112. The distance Z_1 is set at a value which is not equal to the distance from the vertex Z_0 to the focal point Z_{fp}, and preferably set at a value greater than the distance from the vertex Z_0 to the focal point Z_{fp}.

[0064] The connector plug 124 which is affixed to the MMF 12 is fitted into the receptacle 221. As a result, as described with reference to FIG. 8, the light-receiving plane F_{PD2} opposes the output plane F_{out} of the MMF 12 with a distance Z_2 therefrom. Furthermore, the central axis A_{PD} of the light-receiving plane F_{PD2} is aligned with the fiber axis A_{fr}.

[0065] In the optical transmission system S_c as described above, the optical signal OS_{out2} from the MMF 12 is substantially free from the influence of mode dispersion because the input plane F_{in} is positioned at the distance Z_1 from the vertex Z_0. Even if there is any influence of mode dispersion, only the lower-order mode M_{LO} of the optical signal OS_{out2} is selectively received because the light-receiving plane F_{PD2} is positioned at the distance Z_2 from the output plane F_{out}. Therefore, the optical transmission system S_c is capable of further reducing mode dispersion in the MMF 12 as compared to the optical transmission systems S_a and S_b, while eliminating the need for a mode separator 84 (see FIG. 13). Thus, a lower-cost and more broadband-oriented optical transmission system S_c can be provided.

[0066] While the invention has been described in detail, the

foregoing description is in all aspects illustrative and not restrictive. It is understood that numerous other modifications and variations can be devised without departing from the scope of the invention.